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COMPLETE SPECIFICATION

Improved Arrangements for Separating or Separately Detecting Charged Particles of Different Specific Charges

I, WOLFGANG PAUL, of 6, Nussallee, Bonn, Germany, a German citizen, do hereby declare the invention, for which I pray that a patent may be granted to me, and the method by which it is to be performed, to be particularly described in and by the following statement: —

The invention relates to arrangements for separating or separately measuring charged particles of different specific charges, for example ions.

Known arrangements for separating or separately detecting ions of different masses and charges using so-called mass spectrometers or electromagnetic isotope separators operate on the following principle: by simultaneously or successively measuring two of the three quantities impulse, energy, and velocity of the ions, the specific charge e/m (e being the charge and m being the mass of the ions) is determined by eliminating the velocity. When the value of the charge e of the ions is known the value of the mass m results therefrom directly. The two quantities referred to may be measured explicitly or implicitly. When they are measured implicitly it is usual to separate ions of different specific charges from one another in space or in time. In this case,

a) the value of the impulse is measured by deflecting the ions in a static magnetic field;

b) the energy is measured by deflecting or accelerating the ions in a static electric field;

c) the velocity is measured by determining the time required by the ions for moving through a predetermined length of a (rectilinear or curved) path (transit-time spectrometer, omegatron and the like), the transit-time being measured by using known high-frequency measuring arrangements.

For obtaining a high resolving power, the measuring arrangements enumerated above under a and b require narrow slits which reduce the intensity of the ion current, or large dimensions of the measuring arrangement.

The known transit-time arrangements have the following disadvantages:

a) Only those ions are utilized for the measurement which originate within certain short time intervals or which comply with certain phase conditions (so-called impulsing methods). This leads to a considerable loss in intensity rendering the transit-time methods not very suitable for the separation of isotopes.

b) Usually not only ions of a certain value m of the mass (the value of the charge e being known) are recorded, but additionally also such ions are recorded, whose mass value equals m multiplied or divided by 2, $\sqrt{2}$, or the like.

A further arrangement has already been suggested which operates as follows:

The ions are introduced into an electric field which is constant with respect to the time and the potential of which is proportional to x^2, the ions performing harmonic oscillations in the direction of the x-axis. By superimposing a high frequency alternating field, the amplitudes of the oscillations of those ions the natural frequency of which equals the frequency of the alternating field or an integral multiple or sub-multiple thereof increase more and more (owing to resonance) against the action of the static electric field and are thereby separated from the rest.

It is an object of the invention to avoid the disadvantages previously referred to, and generally to provide an improved arrangement for separating or separately measuring charged particles of different specific charges.

The invention consists in an arrangement for separating charged particles having different specific charges, comprising electrodes, means for creating on the said electrodes a voltage which is an arbitrary periodical function f(t) of the time t, the surfaces of the electrodes facing one another being so shaped

that an electric time periodical field is set up such that the potential φ of the field is a general quadratic function

$$\varphi = f(t). \quad (\alpha x^2 + \beta y^2 - \gamma z^2)$$

of the rectangular co-ordinates x, y, z, of the electrodes α, β, γ being positive constants, although α or β may be zero, and satisfying the condition $\alpha + \beta = \gamma$, means for creating ions within, or introducing ions into, the said time-periodical field which causes the ions to oscillate at their natural frequencies in such a manner that ions of a predetermined specific charge oscillate with a limited amplitude while the remaining ions oscillate with an increasing amplitude so that the latter travel in unstable paths, means for varying at least one of the three quantities amplitude, frequency and shape of the voltage f(t) to cause ions to be removed from the field to travel in unstable paths, and means for collecting the remaining ions, which travel in stable paths.

The surfaces of the electrodes facing one another may be of hyperbolical or circular shape when the electrode arrangement is viewed in cross section.

In the equation

$$(1) \quad \varphi(x,y,z,t) = f(t). \quad (\alpha x^2 + \beta y^2 - \gamma z^2)$$

the term f(t) is an arbitrary periodic function of the time t. Because of the Laplacian $\Delta\varphi = 0$ the constants α, β and γ have to satisfy the equation $\alpha + \beta = \gamma$. When the ions are created within, or introduced into, such a field the equations of their movements are differential equations with periodical coefficients, the equations being characterized by having ranges of stable and unstable solutions. Thus, there exist two different kinds of ion paths; either the ions perform oscillations around the centre of symmetry of the field, the amplitudes of the oscillations remaining smaller than a certain maximum value (stable paths), or else the amplitudes of the oscillations increase extremely rapidly so that, within a very short time, the particles impinge on the field generating electrodes and are thus removed (unstable paths). When the field and the dependence on the time f(t) are given, it depends only on specific charge of a particular ion whether it travels along a stable or unstable path. In particular, the stability or instability of the paths is independent of the point of origin and of the direction and magnitude of the initial velocity of the ion. If e/m of the ion lies in a stable range, then all its possible paths are stable and, conversely, if e/m of the ion lies in an unstable range, then all its possible paths are unstable. The positions and widths of the stable ranges of the specific charge can be varied within very wide limits solely by varying the amplitude, frequency and/or shape of the oscillations of the field creating voltages, that is to say by varying the function f(t).

To make the invention clearly understood, reference will now be made to the accompanying drawings, which are given by way of example and in which:—

Fig. 1 illustrates electrodes for use in an arrangement of the invention;

Fig. 2 diagrammatically illustrates a longitudinal section through an arrangement of the invention;

Fig. 3 illustrates a section along the line III—III of Fig. 2;

Fig. 4 is a similar cross-section illustrating differently shaped electrodes;

Fig. 5 is a circuit diagram showing the external connections of the electrodes;

Figs. 6, 7, 8 and 9 are diagrams given for explanatory purposes;

Fig. 10 illustrates a modified electrode arrangement for use in an arrangement of the invention;

Fig. 11 illustrates still another such electrode arrangement; and

Fig. 12 illustrates a longitudinal section through an arrangement employing electrodes similar to those of Fig. 11.

In all the drawings the same reference characters indicate corresponding parts.

The arrangement of electrodes of Fig. 1 serves to create a cylindrically symmetrical electric field. The arrangement comprises four electrodes A,A, B,B of hyperbolical shape in section, the electrodes being arranged at the distance r_o from the x-axis. The two electrodes A are electrically interconnected, and the electrodes B are electrically interconnected. A time-periodical voltage $U = U_o + V \cos \omega t$ is applied between the pairs of electrodes A and B, whereby an electric field is created having a potential $\varphi = (U/r_o^2)(y^2 - z^2)$. This field is independent of x, its centre of symmetry being the x-axis. In this case $\alpha = 0$ in equation (1).

Figs. 2 and 3 show an arrangement comprising a vessel 4, which can be evacuated and in which electrodes 1 are provided whose surfaces facing one another are of hyperbolical shape when viewed in cross-section similar to those of the electrodes of Fig. 1, except that for ease of manufacture the electrodes are not open sided but solid. However, instead of the electrodes shown in Figs. 2 and 3, electrodes of the shape shown in Fig. 1 could alternatively be used. Still alternatively, it is possible and for manufacturing reasons preferable to employ four circularly cylindrical electrodes as shown in Fig. 4 for creating the cylindrically symmetrical electric field with sufficient approximation, the radius of the electrodes of Fig. 4 equalling the radius of curvature of hyperbolical electrode surfaces at the vertices. The error introduced into the potential as defined by equation (1) is, within the space of the stable ion paths, small as compared with errors caused by mechanical manufacturing

tolerances, space charge influences and undesired frequency and amplitude variations so that the stable ion paths are in practice not disturbed by constructing the electrodes as cylinders of circular cross-section. In any case, the electrodes are adjustably mounted in, and insulated from one another by, discs 4[1] of ceramic material. A voltage U is applied between pairs of opposite electrodes by means of leads 2 passing through the wall of the vessel 4 in a vacuum-tight manner. From a conventional ion source 5 (for example an electron impact source or a low-voltage arc discharge), which is connected to the vessel 4 in a vacuum-tight manner by means of flanges, ions to be separated travel in the direction of the arrow 6 into the space between the electrodes 1 with a kinetic energy eU_B. Between the electrodes 1, the ions are separated in accordance with their stability. The ions that have stable paths can travel through the electric field and are collected by a cup-shaped collecting electrode 3, an electrically insulated lead to the collecting electrode 3 passing in a vacuum-tight manner through the wall of the vessel 4 (for example through a sealing boss thereof). The charge on the collecting electrode 3 flows through a resistor 7 to earth and the voltage thereby created across the resistor 7 is measured. Two circular diaphragms 8 respectively screen the source 5 of ions and the collecting electrode 3 against the high-frequency electric field between the electrodes 1.

Fig. 5 illustrates how voltage supply sources are coupled to the electrodes 1. An electric generator 9 creates a high-frequency voltage $V \cos \omega t$ which, by means of two capacitors 14, is applied to the electrodes 1. Moreover, the high frequency voltage is rectified and smoothed by a rectifier 10. The D.C. voltage so created is divided by a potentiometer 15 and is also fed to the electrodes 1 through choke coils 13, the D.C. voltage being $U_o = uV$. Thereby, it is achieved that the ratio u of the D.C. voltage U_o to the A.C. voltage V is substantially independent of alterations of the A.C. voltage. Alternatively, a D.C. voltage may be applied to the electrodes 1 by an independent D.C. voltage source 11 and an electric two-way switch.

The arrangement described operates as follows: —

In the electric field having the potential

$$\varphi = (U(t)/r_o^2)\ (y^2 - z^2)$$

the electric force is

$$E_x = 0;\ E_y = (2U/r_o^2);\ E_z = -(2U/r_o^2)z$$

When U is an A.C. voltage corresponding to the equation $U = V \cos \omega t$, the equations of movement of an ion are as follows:

$$\left.\begin{aligned} \ddot{mx} &= 0; \\ \ddot{my} - (2eV/r_o^2)y \cos \omega t &= 0; \\ \ddot{mz} + (2eV/r_o^2)z \cos \omega t &= 0. \end{aligned}\right\} \quad (2)$$

On integration, the first equation leads to $\dot{x} = \text{const.}$, that is to say, the ion travels in the x-direction with a constant speed. The other two equations are specific cases of the Mathieu differential equation which, in its general shape, is as follows:

$$d^2z/d\xi^2 + (a - 2q \cos \xi)z = 0 \quad (3)$$

The general solution of this equation is as follows:

$$z = Ae^{\mu\xi} \sum_{-\infty}^{+\infty} c_n \cdot e^{+in\xi} + Be^{-\mu\xi} \sum_{-\infty}^{+\infty} c_n \cdot e^{-in\xi}$$

From this it will be recognized that two different kinds of solutions exist. If the characteristic exponent μ, which can be computed from a and q, is imaginary, the solution remains finite for all values of ξ. If, however, μ is real or complex, the amplitude increases exponentially and the path is unstable. Whether the solution is stable or unstable depends only on the value of the parameters a and q, but is independent of the initial values z_o and $\dot{z}_o$ of z. Fig. 6 illustrates the stable ranges in the a, q-plane, the stable ranges being shaded.

From a comparison of equation (2) with equation (3), it will be seen that in the present case

$$a = o; \qquad q = 4eV/r_o^2\ m\omega^2; \qquad \xi = \omega t/2 \quad (4)$$

Thus the ions may be located at any arbitrary point of the q-axis of the diagram of Fig. 6.

Fig. 7 illustrates the vicinity of the q-axis. For clarity, the higher ranges are shown exaggeratedly broad. From $q = 0$ to $q = 0.92$, the ion is in a stable range; from $q = 0.92$ to $q = 7.50$, it is in an unstable range; from $q = 7.50$ to $q = 7.52$, it is again in a stable range; and so on.

When the A.C. voltage and the frequency are given, it depends only on the value of e/m in which range the ion is located, as can be seen from equation (4).

For an A.C. voltage of 1000 volts, the first two stable ranges F_1 and F_2 are shown in a

M, ν-diagram in Fig. 8, the stable ranges being shaded (M being the mass number defined by $e/m_oM=e/m$ and ν being the frequency). From this the following can be recognized: when an ion beam comprises ions of different masses, and when the A.C. voltage and frequency are given, then in the first range those ions only can pass through the field the masses of which are greater than $Mm_o=4eV/0.92\,r_o^2\omega^2$. In the second range, only a finite mass interval $\Delta m = m\Delta q/q$ can pass. Since for the second range $\Delta q/q$ equals approximately 1%, isotopes of comparatively small masses can still be separated. Here it is somewhat disturbing that a mass continuum of the first range is superimposed on the second range. From the third range onwards Δq is very small so that a very good resolution could be expected. However, these ranges can hardly be used because the intensities are too small. As can be verified by computation, the initial energies of the ions in the y- and z-directions must in the third range not exceed the value 10^{-6} eV.

When a D.C. voltage is superimposed on the A.C. voltage that is to say when $U = U_o + V\cos\omega t$, is it possible to achieve that also in the first range only a small mass interval ΔM can pass. The equations of movement now read as follows: —

$$\ddot{y} - (2e/mr_o^2)\,.\,(U_o + V\cos\omega t)y = 0$$
$$\ddot{z} + (2e/mr_o^2)\,.\,(U_o + V\cos\omega t)z = 0 \qquad (5)$$

A comparison of equation (5) with equation (3) shows that

$$a_y = -8eU_o/r_o^2m\omega^2;\ a_z = +8eU_o/r_o^2m\omega^2$$

while again $q=4eV/r^2m\omega^2$ holds for both directions of movement. The ratio $a/q = \pm 2U_o/V$ depends only on the D.C. voltage and the A.C. voltage, but does not depend on the frequency and ion mass. In the a, q-diagram, the lines $u=U_o/V=a/2q$ are rectilinear lines starting at the origin and lying symmetrically to the q-axis. In Fig. 9, a section of the first range of stability and a pair of rectilinear lines $u=$ const. are shown. The half plane $a<0$ corresponds to the y-direction and the half plane $a>0$ corresponds to the z-direction.

When it is assumed that the D.C. voltage and the amplitude and frequency of the A.C. voltage are kept constant, all the masses lie on the rectilinear lines $u=$const. the mass m_1 corresponds to the value q_1 and it is $q_2 \triangleq m_2$ and $q_3 \triangleq m_3$. In the y-direction, only the mase from m_1 to m_6 fall into a stable range, and in the z-direction, only masses exceeding m_2 fall in a stable range. The lines a_0 and b_1 in Fig. 9 are not to be confused with the rectilinear lines $u=U_o/V=a/2q$. The lines a_0 and b_1 are lines limiting the first stable range. They are defined by those pairs of values for which the general solution of the equation (3) just remains finite. They thus form the limiting lines for the stable range under consideration. From theoretical considerations the following equations can be obtained for the first stable range:

$$a_0 \overset{\sim}{=} \tfrac{1}{2}q^2 + \frac{7}{128}q^4 + kq^6 + \ldots$$

$$b_1 \overset{\sim}{=} 1 - q - \tfrac{1}{8}q^2 + \frac{1}{64}q^3 - \frac{1}{1536}q^4 + \bar{k}.q^5 + \ldots$$

The coefficients of q^6 and q^5 are practically equal to zero. Since an ion can pass through the electric field only if it is stable in the y-direction as well as in the z-direction, the result is that only a mass interval $\Delta m = m_1 - m_2$ can pass through the field. When the D.C. voltage is increased, the angle between the rectilinear lines and the q-axis is increased and thereby the pass range is narrowed. For the ratio $U_o/V=0.166$, an infinitely small range results in the limiting case. Above this value no ion can pass through the field. In this case, q assumes the value $q_{max}=0.706$. The width of the stable range in dependence on the D.C. voltage is obtained from the points of intersection of the rectilinear lines $u=$ const with the limiting curves of the first range of stability. From rather complicated theoretical considerations it follows that in the vicinity of the point $q=q_{max}$ it is

$$\Delta q \approx 4(0.236 - 1.410u),$$

and that at constant field quantities, this corresponds to a mass range

$$\Delta m = 4\ mq^{-1}(0.236 - 1.410u).$$

From this, the theoretical mass revolution can be computed as a function of the quantity u; it is

$$m/\Delta m = (\tfrac{1}{2})\,(\nu/\Delta\nu) = 0.75/(1 - u/u_{max}).$$

In the foregoing, it has been assumed that the electric field is infinitely long in the x-direction since only for $t\to\infty$ the amplitudes of the unstable ion paths approximate ∞. In practice it is, however, sufficient to postulate that the ions are subjected to so many alternations of the electric field that the amplitudes of the unstable paths increase sufficiently for the ions to impinge on the electrodes creating the electric field. Thus, it is only necessary to make the length L of the electric field so great that the time while the ions are within the

field is large as compared with the duration of a single high-frequency period. The high-frequency period is $\tau = L/v$ when the velocity of the ions is $v = \sqrt{2eU_B/m}$, U_B being the accelerating voltage. This expression has to be great as compared with $1/\nu$ that is to say

$$L > r_o \pi \sqrt{2U_B q/V}.$$

For $L = 50$ cm., $r_o = 0.5$ cm. and $V = 1000$ volts, the number of field alternations is $n = 850/U_B$. 100 V-ions, thus, are subjected to 85 field alternations, 1000 V-ions only to 25, a value for which it is doubtful whether the amplitudes of the wrong masses have already increased to such an extent that they do no longer reach the collecting electrode.

From the foregoing it will be seen that the cylindrically symmetrical arrangement can be used as a mass spectrometer having an adjustable pass range and as an isotope separator. The arrangement using circularly cylindrical electrodes allows a convenient, material-saving and energy-saving multiplication of the separating arrangement in order to obtain high intensities, wherein circularly cylindrical electrodes are effective in a plurality of individual arrangements. Fig. 10 illustrates electrodes forming such an assembly of circularly cylindrical electrodes A and B; all the electrodes A are conductively interconnected and all the electrodes B are likewise conductively interconnected.

Fig. 11 shows another construction of the electrodes. In this case, the potential is

$$\varphi = (U/r_o^2)(x^2 + y^2 - 2z^2);$$

thus, in equation (1) it is for this case

$$\alpha = \beta = \tfrac{1}{2}\gamma.$$

Fig. 12 illustrates a section through an arrangement using the electrodes of Fig. 11. The electric field is created by three electrodes A, B, B, the adjacent surfaces of the three electrodes forming a one-part hyperboloid of revolution and a two-part hyperboloid of revolution, the assymptotic cones having an apex angle δ of 109.47° ($\tan(\delta/2) = \sqrt{2}$). The electrodes B are conductively interconnected; between the electrode A and the pair of electrodes B, the time-periodical voltage U is applied. The electrodes are arranged in a vessel 16, which can be evacuated through a tube 21, leads to the electrodes passing through the wall of the vessel in a vacuum-tight manner, and in which the electrode A is held by an insulating support 22. For creating ions in the space between the electrodes, a gas to be tested is introduced into the arrangement at a low pressure. An incandescent cathode is indicated by reference numeral 17; electrons emitted by the cathode 17 pass into the space between the electrodes through holes 18 in one of the electrodes B. For focusing the electrons, an electrode 19 is provided, which is negatively biased relatively to the cathode 17. The electrons ionize the gas in the ionization space 20 between the electrodes.

When again, a potential $U_o + V\cos\omega t$ is applied between the electrode A and the pair of electrodes B, ions of the stable e/m-range remain between the electrodes while ions of the unstable range impinge on the electrodes. The ions can, thus, be detected either as a lagging load in the alternating current circuit if they are in the stable range, or as a non-reactive load if they are in the unstable range, since in the later case they act as an ohmic resistance. In order to increase the measuring accuracy in the latter case, it is possible to embed a small unstable range in the stable range, the width of which increases with the amplitude, by superimposing an additional alternating voltage of small amplitude and half the frequency. This can be recognised by the following considerations: As explained above, the separating effect of the arrangement is based on the fact that ions of different values of e/m move under suitable conditions in different manner in the electric field. The electrodes limit the amplitudes of the ions and allow only such ions to pass through the field the amplitudes of which do not exceed the electrode distance. Such ions pass in stable paths. It is thus possible to cause one kind of ions to pass through the arrangement along stable paths, and to cause other kinds of ions to move along unstable paths. For stable ranges, the solution of equation (3) may be written as follows:

$$z = Az_1 + Bz_2 = A\sum_{-\infty}^{\infty} c_{2n}\cos(2n+\beta)\xi + B\sum_{-\infty}^{\infty} c_{2n}\sin(2n+\beta)\xi$$

wherein A and B are constants of integration and β is the constant of frequency. (See also the text book by N. W. McLachlan, Theory and Application of Matthieu Functions, Clarendon Press, Oxford, 1947). From this, one obtains

$$z_1 = c_0\cos\tfrac{1}{2}\beta\omega t + \sum_1^{\infty}\left[c_{2n}\cos(n+\tfrac{1}{2}\beta)\omega t + c_{-2n}\cos(n-\tfrac{1}{2}\beta)\omega t\right]$$

$$z_2 = c_0\sin\tfrac{1}{2}\beta\omega t + \sum_1^{\infty}\left[c_{2n}\sin(n+\tfrac{1}{2}\beta)\omega t + c_{-2n}\sin(n-\tfrac{1}{2}\beta)\omega t\right]$$

The spectrum of movement comprises the frequencies

$$\omega_r = (n + \tfrac{1}{2}\beta)\omega,\ n = 0,\ 1,\ 2,\ \ldots$$

The spectrum as well as the amplitude coefficients c_{2n} depend only on a and q but do not depend on the initial conditions. When U, V and ω are fixed, then ions of different values of e/m belong to different values of a and q. The spectrum of movement thus is independent of e/m. If now on the original electric field an essentially weaker additional field of a frequency $\omega' = \frac{1}{2}\beta\omega$ is superimposed, the following can be expected. Ions of the basic frequency ω' oscillate with their natural frequency and, notwithstanding the weakness of the additional field, their amplitude will permanently increase. Ions of a slightly different value of e/m have a different natural frequency and will oscillate with the beat frequency, which may be the difference of the natural frequency of the ions and the frequency of the additional field. Their amplitudes remain finite. Thus, it becomes possible to filter out ions of a certain mass from a mixture of isotopes. The same effect can be expected if a higher frequency of the spectrum of movement is in resonance with the frequency of the additional field. The movement of the ions is defined by the equations

$$m\ddot{x} = 0$$

$$m\ddot{y} = e(U_0 + V\cos\omega t + V'\cos\omega' t)\frac{y}{r_0^2} = 0$$

$$m\ddot{z} + e(U_0 + V\cos\omega t + V'\cos\omega' t)\frac{z}{r_0^2} = 0$$

These equations are Hill's differential equations which embrace the Matthieu equations as a specific case. Also in the general case of Hill's equations, stable and unstable ranges are obtained in the a-q-plane, which are somewhat displaced relatively to the previous ranges. Now, in this case unstable ranges occur within the stable ranges. These unstable ranges lie at zones where the frequency of the additional field coincides with the natural frequencies of movements of the ions and have a width depending on the amount of the disturbance. Thus from an ion mixture with closely adjacent values of e/m ions of a predetermined value of e/m can be separated with a particularly high resolution, the separated ions reaching in this case the electrodes. This rotationally symmetrical arrangement can be used as a mass spectrometer.

In connection with both field arrangements, namely the cylindrically symmetrical arrangement of Fig. 2 and the rotationally symmetrical arrangement of Fig. 12, the sinusoidal periodicity is only one possible form of the oscillations. The method may alternatively be performed by using oscillations of different shapes. The position of the stable and unstable ranges is hardly affected by the shape of the oscillations.

The arrangements of the invention are distinguished from other arrangements using a high frequency electric field especially by the feature that in the present case this field is not utilized for measuring a transit time of the ions. Consequently, the present arrangements are independent of the phase at which the ions enters the electric field so that the arrangements of the invention do not require impulsing and the separation of ions of different specific charges may be effected continuously.

The arrangements of the invention are furthermore distinguished from the previously suggested arrangement by the feature that the static electric field (that is to say the time mean value of the time-periodical field), if provided at all, is only an auxiliary field for varying and narrowing the stable range, but is not, as previously, necessarily required for causing the ions to oscillate harmonically as in the case with the previously suggested method. Consequently, in the method of the present invention the direct voltage is considerably lower than the peak value of the high frequency alternating voltage while conversely in the previous method the alternating voltage had to be considerably lower than the direct voltage. Moreover, no magnetic field for additionally focusing the ions is required since, averaging over the time, no de-focusing forces act on the ions in the stable range. The advantages of the invention as compared with the known arrangements are essentially the following: —

1.) A great simplification of the arrangement is achieved. Since an electric alternating field of only moderate voltage and frequency is required, the arrangement may be much simpler than previously known arrangements.

2.) An independence from the initial condition is achieved. Since the operation of the arrangement is independent of the direction and the value of the initial velocity of the ions, ion sources may be used which create ions of highly different velocities without thereby impairing the resolution, that is to say the accuracy of separation. The resolution is defined for ions of known charge by the expression $m/\Delta m$, m being the mass of ions to be detected and Δm the mass difference between other ions which can be separated from the ions to be detected. Since with most of the known methods only ions within narrow ranges of directions and velocities can be used for the measurement, a considerable gain of intensity results in comparison with those methods so that the requirements on the sensitivity of the detecting means may be considerably lowered. High intensities (that is to say high ion currents) are of especial advan-

tage in arrangements for separating isotopes.

3.) A convenient control is achieved of the position and width of the stable and unstable ranges by only varying the frequency, amplitude and/or shape of the field-creating voltages. Thus, in an arrangement after it has been set up, the measuring range and the accuracy may yet be varied within wide limits.

The advantages of the arrangement as compared with transit-time spectrometers are especially the following: —

4.) Since the present method is independent of the initial conditions (see paragraph 2 above) it is not necessary to use impulsing or to comply with phase conditions.

5.) It is easily achieved that of ions of a known charge only those of a well defined mass are recorded. Disturbances by masses which are multiplied or divided by 2, $\sqrt{2}$, or the like, can be avoided without difficulty.

6.) Ions in the stable range are not affected in any direction by defocusing forces when averaging over the time; thus additional magnetic fields for focusing the ions are not required.

A further advantage of the arrangement of the invention resides in the fact that practically no ions accumulate in the space between the electrodes, which could give rise to space charges.

The arrangements of the invention may find many applications such as: —

I. Use for mass analysis.

Since, as indicated above, by means of the present methods ions of different specific charges can be separated or separately detected, the methods may be employed for constructing a mass spectrometer. Suitable for this purpose are the cylindrically symmetrical, as well as the rotationally symmetrical electric fields described hereinbefore.

II. Use for separating isotopes.

Since, as explained above, the present procedure allows high intensities (that is to say high ion currents), it may be employed for constructing plants for separating isotopes. For this purpose the cylindrically symmetrical electric field is particularly suitable.

III. Use as a pressure gauge for measuring partial pressures of components of highly rarified gas mixtures.

For example, the ionized gas mixture is introduced into the rotationally symmetrical field; individual components of the mixture are successively detected or quantitatively measured by correspondingly displacing the ranges of stability and instability. The advantages of such a pressure gauge as compared with hitherto usual pressure gauges are, amongst others, the compactness of the arrangement (linear dimensions of a few centimeters are sufficient) and the possibility of easy heating (the arrangement consists essentially of three metal electrodes).

IV. Use for finding leakages in vacuum devices.

The vacuum device is introduced into an atmosphere which contains traces of gases usually not contained in the air. If such traces enter into the vacuum devices through a leakage it is easy to detect the same by means of a pressure gauge in the manner explained in the preceding paragraph III.

V. Separating gas mixtures as well as mixtures of liquids and solids in the vapour phase.

The gas or vapour mixtures are ionized and separated by a cylindrically symmetrical field similarly as explained in paragraph II with respect to isotopes. An advantage of this method as compared with separation by distillation or sublimation resides in the feature that the mixture can be separated even if two or more components of the mixture have the same vapour pressure or the same boiling point.

VI. Use for analysing traces.

The mass spectrometer described in paragraph I may also be employed for analysing traces.

VII. Use for measuring low vapour pressures especially of mixtures.

The pressure gauge described in paragraph III may be employed also for measuring low vapour pressures.

What I claim is: —

1. An arrangement for separating charged particles having different specific charges, comprising electrodes, means for creating on the said electrodes a voltage which is an arbitrary periodical function f(t) of the time t, the surfaces of the electrodes facing one another being so shaped that an electric time periodical field is set up such that the potential φ of the field is a general quadratic function

$$\varphi = f(t). \quad (\alpha x^2 + \beta y^2 - \gamma z^2)$$

of the rectangular co-ordinates x, y, z, of the electrodes α, β, γ being positive constants, although α or β may be zero, and satisfying the condition $\alpha + \beta = \gamma$, means for creating ions within, or introducing ions into, the said time-periodical field which causes the ions to oscillate at their natural frequencies in such a manner that ions of a predetermined specific charge oscillate with a limited amplitude while the remaining ions oscillate with an increasing amplitude so that the latter travel in unstable paths, means for varying at least one of the three quantities amplitude, frequency and shape of the voltage f(t) to cause ions to be removed from the field to travel in unstable paths, and means for collecting the remaining ions, which travel in stable paths.

2. An arrangement as claimed in claim 1, wherein the surfaces of the electrodes facing one another are of hyperbolical shape when

the electrode arrangement is viewed in cross section.

3. An arrangement as claimed in claim 1, wherein the surfaces of the electrodes facing one another are of circular shape when the electrode arrangement is viewed in cross section.

4. An arrangement as claimed in claim 1, 2, or 3, for separately measuring charged particles having different specific charges, wherein means are provided in a circuit comprising the collecting means for measuring the ion current of those ions which travel in stable paths.

5. An arrangement as claimed in any of claims 1 to 4, wherein the means of creating the voltage on the electrodes are such that the voltage

$$f(t)=U_o+V\cos\omega t,$$

U_o being a D.C. voltage and V the amplitude of an A.C. voltage, the ratio U_o/V determining a stable range of ion paths.

6. An arrangement as claimed in claim 5, wherein means are provided for varying the ratio U_o/V and thereby the width of the stable range.

7. An arrangement as claimed in claim 5 or 6, wherein four parallel electrodes are provided for creating a cylindrically symmetrical electric field, the pairs of opposite electrodes being conductively interconnected so that the electric field has a potential

$$\varphi=(U_o+V\cos\omega t)\,(y^2-z^2)/r_o^2,$$

r_o being the distance of the electrodes from the X-axis.

8. An arrangement as claimed in claim 7, wherein an arbitrary number of pairs of additional electrodes are provided for multiplying the separating effect.

9. An arrangement as claimed in any of claims 1 to 4, wherein the field-creating electrodes are such that the time-periodical electric field has a potential

$$\varphi=(U_o+V\cos\omega t)\,.\,(x^2+y^2-2z^2/r_o^2,$$

U_o being a D.C. voltage and V the amplitude of an A.C. voltage, whereby the said field is rendered rotationally symmetrical.

10. An arrangement as claimed in any of claims 1 to 9, wherein means are provided for measuring a load caused by the ions in an alternating current circuit for creating the said electric field, ions travelling in stable paths being detected or measured by ascertaining or measuring the load as a lagging load.

11. An arrangement as claimed in claim 10, wherein means are provided for deriving a main A.C. voltage from the alternating current circuit and for superimposing an additional A.C. voltage of an amplitude that is small as compared with that of the main A.C. voltage and of half the frequency of the main A.C. voltage on the said main A.C. voltage, whereby a small unstable range of ion paths is embedded in a broad stable range of ion paths.

12. An arrangement for detecting a leakage in a vacuum device, wherein means are provided for surrounding the vacuum device with a gas normally not contained in air so that the said gas is given an opportunity to enter the vacuum device through its leakage if present, and means for effecting a communication between the interior of the vacuum device with an arrangement as claimed in claim 4 for measuring the partial pressure of the said gas in the vacuum device is present therein.

13. Arrangements for separating or separately measuring charged particles having different specific charges, constructed, arranged and adapted to operate substantially as hereinbefore described with reference to, and as illustrated in, the accompanying drawings.

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773,689 COMPLETE SPECIFICATION
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SHEETS 1 & 3

Fig.1

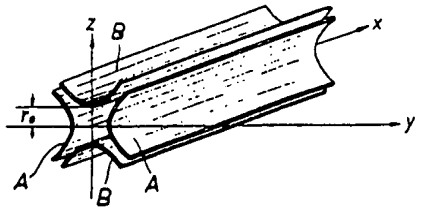


Fig.2

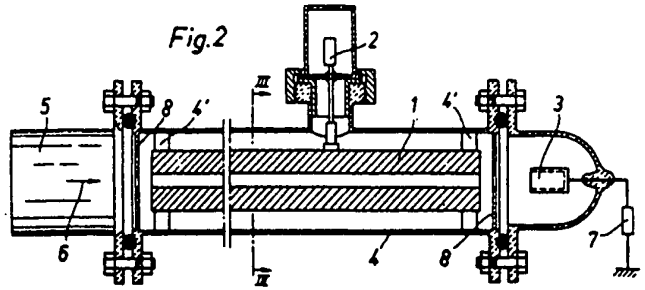


Fig.3

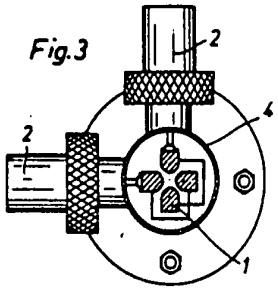


Fig.4

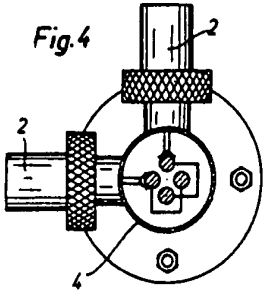


Fig.8

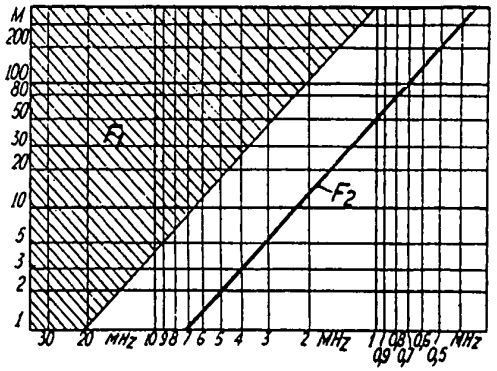
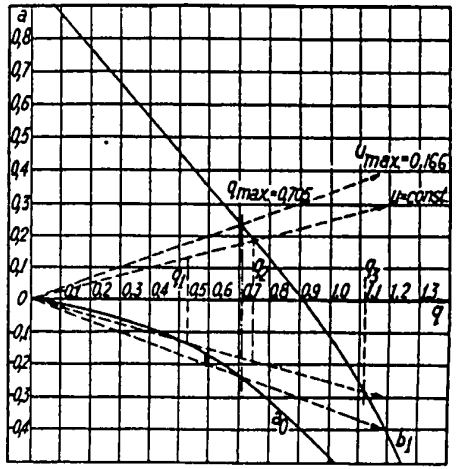


Fig.9



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SHEETS 2 & 4

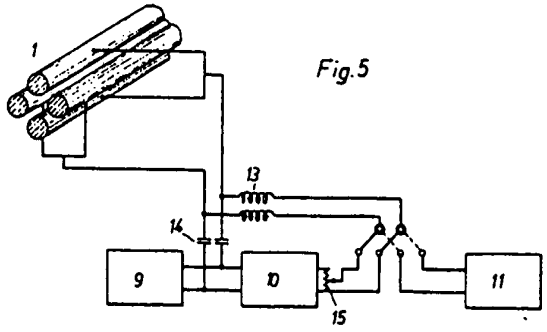

Fig.5

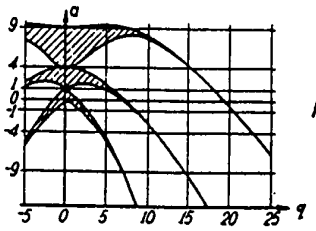

Fig.6

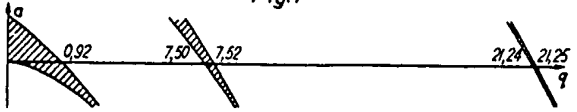

Fig.7

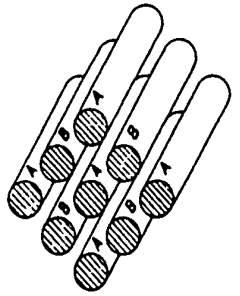

Fig.10

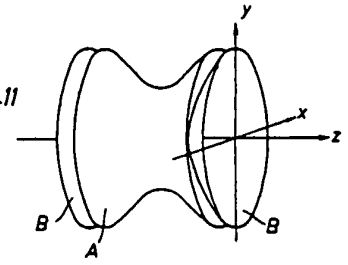

Fig.11

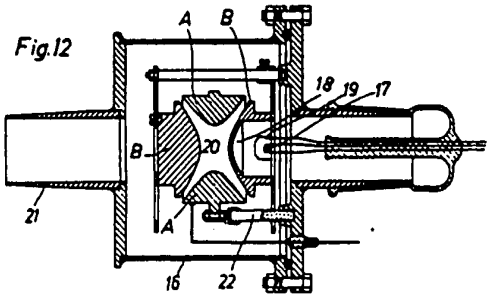

Fig.12